Recent trends in hydrologic balance have enhanced the terrestrial carbon sink in the United States

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[1] Climate data show significant increases in precipitation and humidity over the U.S. since 1900, yet the role of these hydro-climatic changes on the reported U.S. carbon sink is incompletely understood. Using a prognostic terrestrial ecosystem model, we simulated 1900–1993 continental U.S. carbon fluxes and found that increased growth by natural vegetation was associated with increased precipitation and humidity, especially during the 1950–1993 period. CO_2 trends and warmer temperatures had a lesser effect. Two thirds of the increase in observed forest growth rates could be accounted for by observed climatic changes, including the confluence of earlier springs and wetter autumns leading to a lengthening of the vegetation carbon uptake period. However, regional differences in precipitation trends produced differing regional carbon sink responses. The strong coupling between carbon and hydrologic cycles implies that global carbon budget studies, currently dominated by temperature analyses, should consider changes in the hydrologic cycle. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1833 Hydrology: Hydroclimatology; 1836 Hydrology: Hydrologic budget (1655); 1620 Global Change: Climate dynamics (3309); 1851 Hydrology: Plant ecology

1. Introduction

[2] Terrestrial ecosystems in the United States reportedly sequester a large amount of atmospheric CO_2, although accurately quantifying this sink has been difficult [*Pacala et al.*, 2001]. The mechanisms behind the sink, including growth enhancement due to changes in climate, CO_2 fertilization, N deposition, and land-use changes such as forest re-growth, fire suppression, and woody encroachment, are not disputed. However, their relative contributions to the overall carbon sink are not agreed upon [*Houghton et al.*, 1999; *Idso et al.*, 1999; *Nadelhoffer et al.*, 1999; *Caspersen et al.*, 2000; *Schimel et al.*, 2000].

[3] Changes in the global hydrologic cycle are a possible consequence of increasing concentrations of atmospheric greenhouse gases [*Houghton et al.*, 2001]. Analyses of climatic data since 1900 over the continental U.S. show increases in precipitation [*Karl and Knight*, 1998], specific humidity [*Ross and Elliott*, 1996], soil moisture [*Robock et al.*, 2000] and stream flows [*Lins and Slack*, 1999], indicating an altered hydrologic cycle. Many of these hydro-climatic changes directly influence processes involved in carbon uptake (photosynthesis) and release (respiration) from vegetated areas. Whether an active hydrologic cycle results in carbon sequestration (positive uptake) by terrestrial ecosystems, however, is dependent on complex interactions between ecosystem physiology and both the magnitude *and* timing of changes in hydro-climatic conditions. Given the strong coupling between carbon and hydrologic cycles and reported changes in hydro-climatic conditions, we ask the question: Have observed long-term changes in the hydrologic cycle increased carbon sequestration by U.S. natural vegetation?

2. Data and Methods

[4] We used a mechanistic terrestrial ecosystem model, Biome-BGC, with climate, soil and vegetation data sets from the Vegetation/Ecosystem Modeling and Analysis Project [*Schimel et al.*, 2000; *Kittel et al.*, 1995] to compute daily carbon, water and nitrogen fluxes. Briefly, VEMAP derived daily climate data from 1900–1993 using monthly precipitation and temperature records statistically interpolated both in time and space to produce continuous grids at 0.5° latitude/longitude resolution over the continental U.S. Methods for deriving daily humidity and incident solar radiation, and procedures used for developing vegetation type and soils data are described in *Kittel et al.* [1995]. A satellite derived land cover map was used to separate aerial extents of natural vegetation from crop-lands in each 0.5° grid cell for estimating continental scale total fluxes from natural vegetation [*Schimel et al.*, 2000]. Modeled fluxes thus represent potential conditions, as they did not include stand age, disturbance history, or carbon export from ecosystems.

[5] Details of Biome-BGC model theory and the parameterization scheme derived from extensive literature survey of ecophysiological parameters for temperate vegetation are available elsewhere [*Thornton et al.*, 2002; *White et al.*, 2000]. Using the pre-industrial VEMAP climate dataset, the model was run to equilibrium conditions for all natural vegetation types within each grid cell. Applying carbon and nitrogen state variables from these pre-industrial equilibrium conditions, we ran the model from 1900–1993 with daily climate, incorporating changes in annual atmospheric CO_2 and industrial N deposition. Another model run was performed without incorporating anthropogenic changes (CO_2 & N) to isolate the role of changes in the hydrologic cycle. Unless mentioned otherwise, results are presented for model runs incorporating anthropogenic changes.

[6] We first reduced daily climate fields as well as model output fields (evapotranspiration, ET; total net primary production, NPP; heterotrophic respiration, Rh; and net ecosystem production, NEP, defined as NPP-Rh) to monthly and annual values. Next, to accommodate potential differences in the timing of growing seasons across the continental U.S., we calculated May through October (MO) and November through April (NA) values. We then performed linear trend analysis on both climate and model outputs at monthly, seasonal and annual time scales.

[7] We used ground based net primary production (NPP) estimates from two different sources. First, to show the sensitivity of plant growth to temperature and precipitation, we obtained estimates of above-ground NPP (ANPP) and site climate from Long Term Ecological Research (LTER) sites across the continental U.S. [*Knapp and Smith*, 2001]. The LTER network collected

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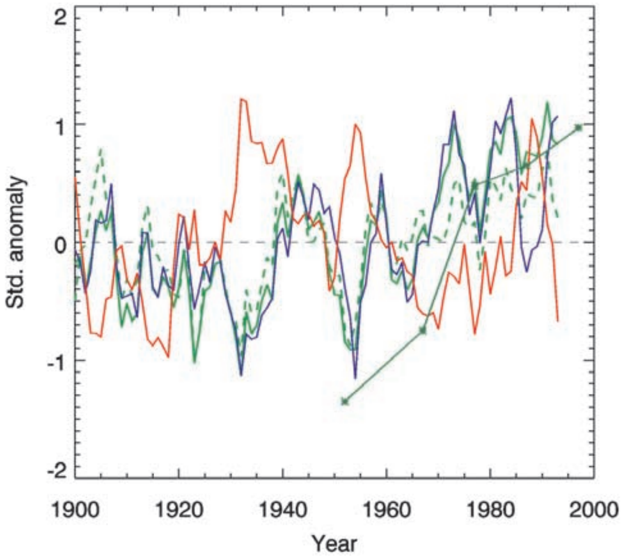

Figure 1. Long-term variations (1900–1993) in annual averages of conterminous U.S. climate (air temperature, red; precipitation, blue) and simulated carbon cycle variables (net primary production, solid green; net ecosystem production, dashed green) smoothed with a 5 point binomial filter. Ground based estimates of net primary production (green with symbols) are derived from national forest assessments reported between 1952 and 1997.

ANPP data over a period of 12–20 years at a number of sites representing a variety of vegetation and climatic conditions. Second, to verify our modeled NPP, we used 1947–1997 continental scale NPP estimates derived from the U.S. Forest Service forest growth inventory [*Hicke et al.*, 2002]. The Forest Service converted forest growth rates to ANPP using allometric relations between growth increments and total wood production. They used litterfall data from a wide bioclimatic gradient to predict fine root production and then calculated total NPP as the sum of above- and below-ground NPP [*Hicke et al.*, 2002].

3. Results and Discussion

3.1. Long-term Changes in Climate and Carbon Cycling

[8] During the 20th century, the U.S. climate showed considerable variability with a modest positive trend in precipitation (0.56 mm/y, $p = 0.008$) but no trend in temperature (Figure 1). At the continental scale, across a variety of climate, soil and vegetation types, inter-annual variations in modeled carbon cycle components (NPP and Rh, g C/m^2/y) and precipitation (P, mm/y) were highly correlated ($NPP = 0.45 * P + 70.4$, $R^2 = 0.62$, $p < 0.001$; $Rh = 0.24 * P + 186.6$, $R^2 = 0.66$, $p < 0.001$). Similarly strong relationships were found between P and NPP estimates without incorporating CO_2 fertilization ($NPP = 0.40 * P + 97.0$, $R^2 = 0.58$, $p < 0.001$; $Rh = 0.22 * P + 200$, $R^2 = 0.69$, $p < 0.001$). Variations in temperature (T) did not influence continental NPP or Rh ($NPP = -17.1 * T + 585.0$, $R^2 = 0.04$; $Rh = -5.2 * T + 416.7$, $R^2 = 0.01$). Observed relations between ANPP and climate at LTER sites also confirmed the critical role played by precipitation ($ANPP = 0.45 * P + 31.3$, $R^2 = 0.69$, $p < 0.001$) relative to temperature ($ANPP = -19.47 * T + 564.9$, $R^2 = 0.11$). Between 1950 and 1993, increases in continental average precipitation were substantial (8% or 1.39 mm/y, $p = 0.045$). We also observed a strong negative correlation between annual precipitation and annual vapor pressure deficit ($VPD = -0.538 * P + 1318$, $R^2 = 0.64$, $p < 0.001$). VPD decreased by 5% (−1.02 Pa/y, $p = 0.017$) over the same period. Therefore, increases in precipitation can potentially enhance plant growth both by increasing the supply of and reducing the demand for water. Modeling results showed that anthropogenic changes (CO_2 fertilization & N deposition) enhanced NPP for a given increase in precipitation; however, precipitation remains the primary controlling factor in plant growth.

[9] Simulated forest NPP at the continental scale showed an average increase of 67 g C/m^2/y (from 566 to 633) between 1950–1993, accounting for nearly two thirds of the observed increase in NPP from the national forest assessment (102 g C/m^2, from 415 to 517 between 1952–1997 [*Hicke et al.*, 2002]). Growth stimulation as well as forest re-growth have been previously suggested as possible causes for the increases in observed forest growth rates in the U.S. [*Houghton et al.*, 1999; *Caspersen et al.*, 2000]. Results from this study indicate a larger role for the stimulation of npp due to changes in biophysical environment.

[10] In the presence of CO_2 fertilization, increases in precipitation stimulated NPP more than Rh indicating the potential for larger carbon sinks under wetter conditions. Between 1950 and 1993, NPP increased by 13.6% (0.35 Gt/44y, $p < 0.001$) with a mean NPP of 2.57 Gt/y. The NEP increased by 44% (0.11 Gt/44y, $p = 0.053$) over the same period with a mean of 0.25 Gt/y, and exhibited large inter-annual variation (0.01 to 0.5 Gt/y). Using eddy-covariance observations from forests, *Baldocchi et al.* [2001] concluded that increased carbon sequestration is possible only with increased availability and use of water. Analysis of our results, showing a strong correlation between evapotranspiration and NEP ($NEP = 0.54 * ET - 278.2$, $R^2 = 0.59$), provide further evidence of such a conclusion even at continental scales. A stimulation of NPP, beyond that provided by CO_2 fertilization, is reportedly required in order to explain observed changes in atmospheric CO_2 concentrations and terrestrial carbon pools [*Randerson et al.*, 1997; *Houghton et al.*, 1999]. We believe that changes in the hydrologic cycle may have provided the added stimulus.

3.2. Seasonal Changes in Climate and Carbon Cycling

[11] Changes in carbon cycling also showed significant variation through the year as a consequence of monthly and seasonal trends in continental scale climate and carbon cycling variables. Warmer and wetter spring months first enhanced Rh. Then, as daylengths and incident solar radiation increased in the spring, NPP responded strongly during the months of May and June. Cooler and wetter conditions during September and October further contributed to increased NPP (Figure 2). The net result was an expansion of the carbon uptake period by vegetation, which was shown to be positively related to carbon sequestration [*Baldocchi et al.*, 2001]. The asymmetric changes in modeled NPP and Rh provide further evidence for the reported changes in vegetation activity, seasonality and amplitude of atmospheric CO_2 concentrations [*Houghton*, 1987; *Keeling et al.*, 1996; *Randerson et al.*, 1997; *Myneni et al.*, 1997; *Woodwell et al.*, 1998].

3.3. Spatial Distribution of Changes in Climate and Carbon Cycling

[12] Figure 3 shows that changes in climate and ecosystem responses to such changes were quite variable across the U.S. For example, between 1950 and 1993, continental U.S. air temperatures increased in the west and cooled in the east. On the other hand, annual precipitation showed a general increase over the continent except over the Pacific Northwest. When increases in precipitation coincided with growing season water demands by vegetation, NPP responded positively. Warmer spring temperatures over the Pacific Northwest may have stimulated earlier plant growth [*Cayan et al.*, 2001], but a reduction in precipitation over this region through the year negated their positive impacts on NPP. Stream flow volume records from 1944–1993 also showed decreasing trends in this region [*Lins and Slack*, 1999], a further indication of drought stress during the summer months.

[13] The range of modeled annual average NEP (0–180 g C/m^2/y between 1950–1993) over the continental U.S. is smaller than observed net ecosystem exchange from eddy-covariance towers

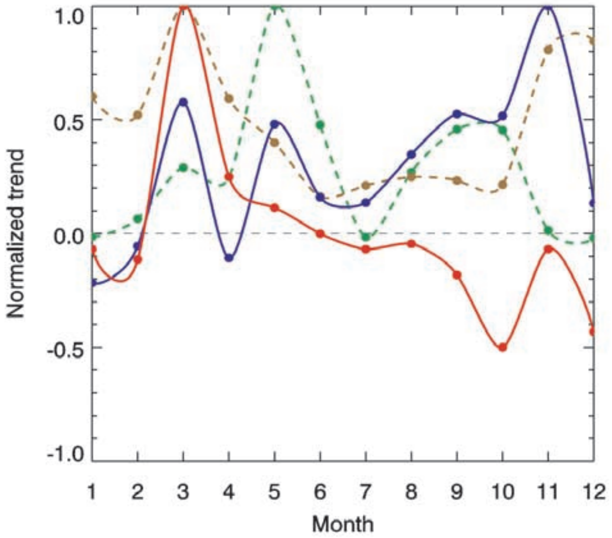

Figure 2. Normalized monthly trends (1950–1993) in continental average precipitation (blue), temperature (red), and simulated NPP (dashed green) and heterotrophic respiration (Rh, dashed dark brown). Monthly trend values are normalized to the maximum trend value in each case: NPP (0.024 Gt/decade), Rh (0.0087 Gt/decade), T (0.44 °C/decade) and P (3.83 mm/decade).

[*Baldocchi et al.*, 2001]. As noted earlier, the quasi-equilibrium conditions simulated by the model better represent relative variations in spatio-temporal dynamics than absolute magnitudes. Forests of the southeastern U.S. led the nation in NEP. Eastern forests, except those in the far southeast and northeast corners, showed the largest increases in NEP following favorable changes in climate. Higher amounts of precipitation and lower VPDs coupled with CO_2 fertilization increased NPP, while cooler temperatures reduced respiration losses. Vegetation of the southwest and interior west regions also showed increases in NEP resulting from higher amounts of precipitation.

[14] Warmer springs in recent decades enabled earlier onset of plant growth and longer growing seasons over Northern Hemisphere mid- and high- latitudes [*Myneni et al.*, 1997; *Cayan et al.*, 2001]. However as *Barber et al.* [2000] reported for Alaskan forests, such increases in temperature limited growing season lengths cannot be readily equated with increases in carbon sequestration if late summer water deficits truncate photosynthetic activity.

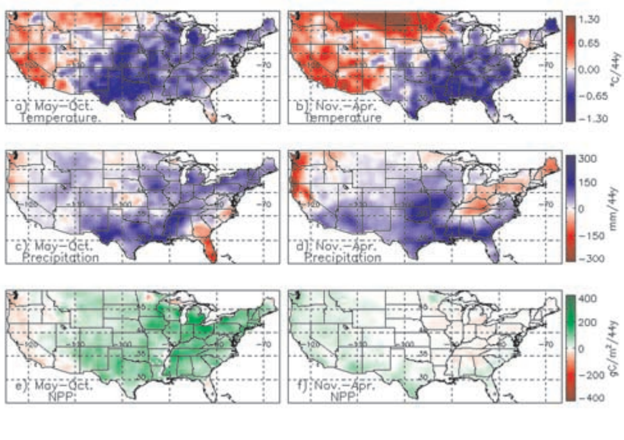

Figure 3. Geographic variation in trends (1950–1993) of temperature, precipitation and simulated NPP for predominant growing seasons in the U.S.

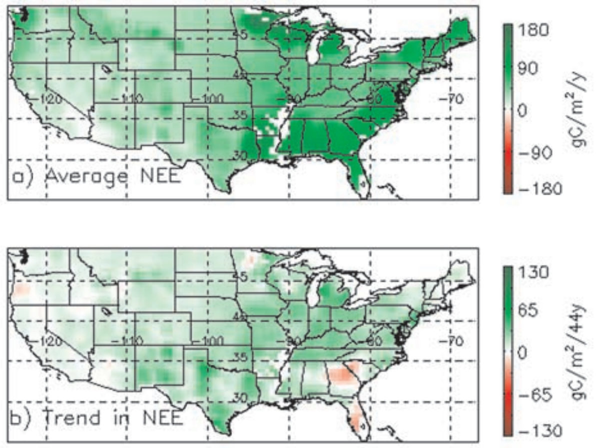

Figure 4. Annual average and trends in net ecosystem production (NEP) from 1950 to 1993 across the continental U.S. for natural vegetation.

Globally, mid- and high-latitude ecosystems benefited from both increased amounts of precipitation and warmer spring temperatures after the mid-1970s, and may have contributed to the well known mid-latitude carbon sink [*Dai and Fung*, 1993; *Dai et al.*, 1997].

[15] Changes in ocean circulation and the ocean-atmosphere tele-connections since the mid-1970s have been identified as possible mechanisms behind recent increases in precipitation over the continental U.S. [*Dai et al.*, 1997]. It is therefore conceivable that future changes in ocean-atmosphere oscillations may alter the current patterns of carbon cycling. The potential for enhanced plant growth from CO_2 fertilization is globally significant, but the ability of a given ecosystem to take advantage of the enriched CO_2 environment depends on optimal climatic conditions. In this context, results from this study show that recent changes in the hydrologic cycle interacted positively with CO_2 fertilization, contributing to higher rates of carbon sequestration over large areas of the U.S.

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